ORIGIN OF THE B-DOT JUMP OBSERVED IN PRECISION LINER EXPERIMENTS

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Abstract

In the liner-ejecta experiments carried out at the Los Alamos pulsed power facility Pegasus II, a solid liner was magnetically imploded to impact on a target cylinder to produce the shock-induced ejecta. As a result of improved time resolution for the B-dot (dB/dt) probes fielded last fall, we began to notice a sharp jump in the B-dot curve occurring at a time very close to the expected liner-target collision time. This jump was also found in the time derivative of the calculated current (dI/dt) obtained from code simulation. We have shown that the jump is indeed caused by the collision as a sudden change of the liner velocity would induce a sudden jump in the time derivative of the inductance. We have derived a general formula for calculating the jump in dI/dt and verified that the result computed from it is in good agreement with the code simulation. Useful diagnostic applications of the B-dot jump are discussed.

Introduction

Precision liner experiments have been carried out at Los Alamos National Laboratory in the last two years using the Pegasus II pulsed power facility. The first series of such experiments has been the liner-ejecta project, in which we use a magnetically imploding solid liner to impact on a target liner and measure the ejecta from the latter produced by the shock. The liner is made of aluminum; its outer radius, thickness, and length are 4.0, 0.04, and 2.0 cm, respectively. The target is also made of aluminum and has an outer radius of 1.5 cm and a thickness of 0.02 cm. A tantalum cylinder, of 1.5 cm in radius and with a semi-circular thin slit, is used as a collimator to restrict the ejecta so that we can measure the velocity and size distributions of the particles with laser holography.

For a detailed description of the experimental setup we refer the readers to two companion papers[1, 2] in this conference. In this paper we would like to discuss the B-dot (dB/dt) jump fortuitously observed in these experiments, and its computational confirmation from the code simulation. We also provide a rigorous physical reasoning how a sudden deceleration of the liner can leads to a sudden jump in dI/dt. We then proceed to derive a general formula for calculating the jump in dI/dt and demonstrate that the result computed from it for the liner-ejecta experiment is in good agreement with the code simulation. Useful diagnostic applications of the B-dot jump are discussed.

Experimental Observation and Code Simulation

The B-dot probes have been fielded together with Rogowski and Faraday rotation current measurements in every liner shot to provide a complete diagnostic coverage. With a more refined B-dot measurement fielded last fall, we began to notice a sharp jump in the B-dot data occurring very close to the expected liner-target collision time. Since dB/dt is proportional to dI/dt, we immediately checked whether the time derivative of the calculated load current, which was obtained from the circuit model built in the 1-D MHD simulation code RAVEN, also exhibited such a jump. It turned out that the calculated dI/dt not only had the jump we were eagerly looking for, but also displayed an additional one right after the liner-target system collided with the collimator. When we looked into the B-dot data the second jump was indeed there, only much broader in width than the first jump. In Fig.1 we display both the measured dB/dt and the calculated dI/dt curves, with their peak value at $t = 0$ normalized to unity for easy comparison.

We notice that both measured jumps are smaller than the corresponding ones from calculation. A more careful examination of the simulation results has indicated that the peaks of the calculated first and

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14. ABSTRACT

In the liner-ejecta experiments carried out at the Los Alamos pulsed power facility Pegasus II, a solid liner was magnetically imploded to impact on a target cylinder to produce the shockinduced ejecta. As a result of improved time resolution for the B-dot (dB/dt) probes fielded last fall, we began to notice a sharp jump in the B-dot curve occurring at a time very close to the expected liner-target collision time. This jump was also found in the time derivative of the calculated current (di/ dt) obtained from code simulation. We have shown that the jump is indeed caused by the collision as a sudden change of the liner velocity would induce a sudden jump in the time derivative of the inductance. We have derived a general formula for calculating the jump in di/dt and verified that the result computed from it is in good agreement with the code simulation. Useful diagnostic applications of the B-dot jump are discussed.

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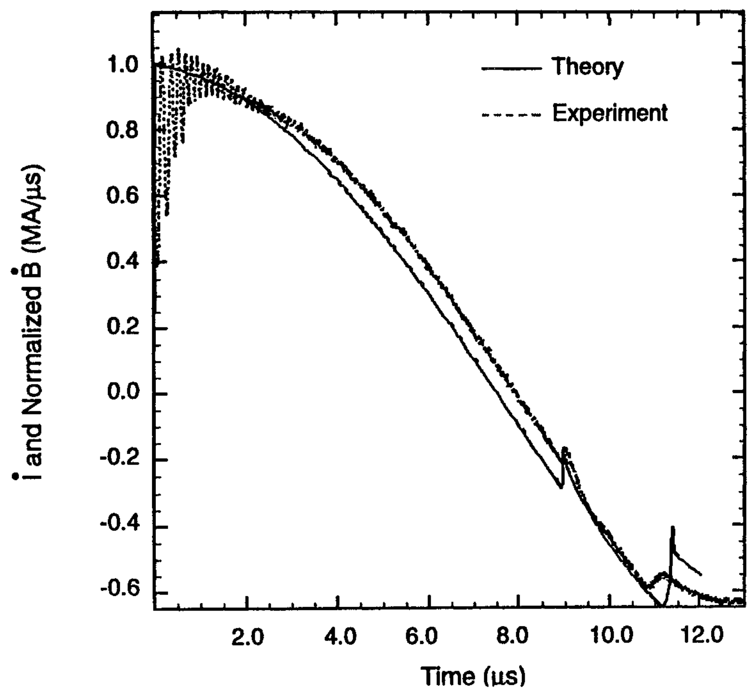

Fig. 1. Measured dB/dt and calculated dI/dt normalized to unity at $t = 0$.

second jumps are 80 and 370 ns, respectively, after the corresponding collisions. These time delays will be understood after we explain the physical mechanism and derive the formula for the jump in the next two sections.

It should be pointed out that if we just look at the calculated current as shown in Fig.2, the curve appears so smooth to the naked eye that we would hardly suspect any sharp jump in its derivative. Besides, in the past the B-dot data, which exhibit large high-frequency noises at the beginning of the bank discharge, were routinely time-integrated to compare with the calculated and other measured currents; so there wasn't any need or interest to compare them with dI/dt directly. Thus even though the jumps in dI/dt were hiddened in the calculated currents long before we were able to observe them through improved time-resolution, ironically we missed the more exciting opportunity to have predicted the jump in dI/dt from calculation.

Physical Origin of the Jump

The physical reason for the B-dot jump can be understood as caused by a sudden jump in dL/dt, where L is the total inductance, resulting from the sudden deceleration of the liner at each collision. To simplify the physics, let us consider the current being carried by an infinitesimally thin liner. For such a liner, the collision is instantaneous and the velocity has a sudden jump. The imploding current for the Pegasus liner can be represented quite accurately by a single loop circuit equation as follows:

$$V = \frac{1}{C}\int_0^t I(t')dt' + R(t)I(t) + \frac{d}{dt}[L(t)I(t)], \tag{1}$$

where V is the initial bank voltage, C the capacitance, and R the total resistance whose time dependence comes from the fuse used to damp the voltage reversal. The inductance L is given by the expression

$$L(t) = L(0) + L_\ell log[r_0/r(t)], \tag{2}$$

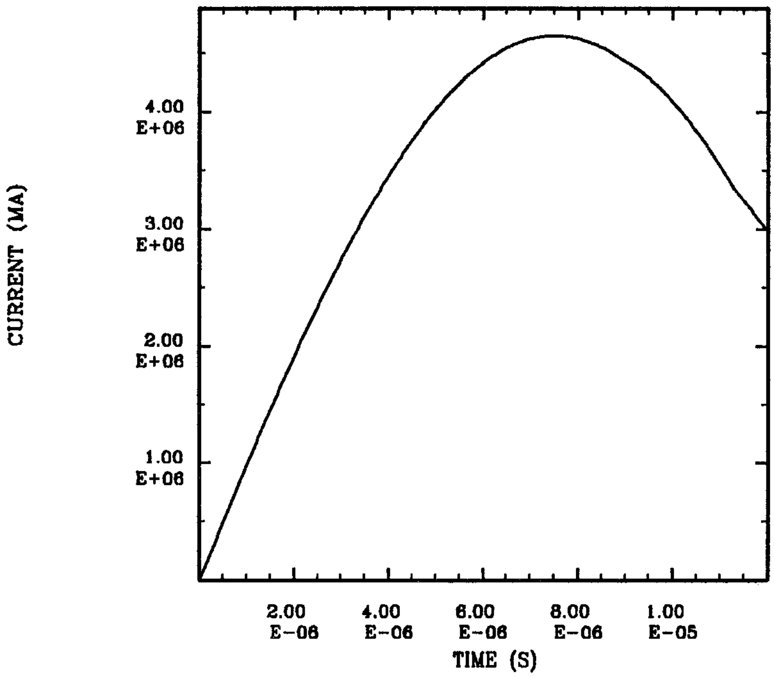

Fig. 2. Imploding current from code calculation.

where $L_\ell = (\mu_0 \ell / 4\pi)$, μ_0 is the vacuum permeability, $r(t)$ the liner radius, r_0 its initial radius, and ℓ its length. First we note that $L(t)$ is a continuous function everywhere since $r(t)$ is. If we integrate Eq.(1) over t term by term and express $I(t)$ as

$$I(t) = \frac{1}{L(t)} \left[Vt - \int_0^t dt \int_0^t I(t')dt' - \int_0^t R(t)I(t)dt \right],$$

we see that $I(t)$ must be a continuous function whenever $L(t)$ and $R(t)$ are. It follows from Eq.(1) that its last term should also be continuous since all the other terms are. However, $\dot{L}$ has a jump at collision as Eq.(2) implies $\dot{L} = -L_\ell \dot{r}/r$ and the velocity $\dot{r}$ does have a jump. Evaluating Eq.(1) right after and just before the collision and taking the difference, we get the exact jump relation

$$L\Delta\dot{I} + I\Delta\dot{L} = 0, \tag{3}$$

hence the jump in $\dot{I}$ is related to the jump in velocity by

$$\Delta\dot{I} = (IL_\ell / rL)\Delta\dot{r}. \tag{4}$$

General Formulation and Discussions

Once we understand how a sudden radial deceleration (acceleration) of an infinitesimally thin liner can give rise to a positive (negative) jump in $\dot{I}$, it is then straightforward to work out the more general case for a liner with finite thickness and realistic material properties. For such a liner, the current may not be uniformly distributed across its thickness in general because the current has to diffuse from outside in. Furthermore, the Joule heating from a non-uniform current distribution will give rise to a non-uniform distribution in temperature, density, and conductivity as well. Consequently, the collision shock speed and deceleration may not stay constant across the liner either.

Let $r(t)$ be the inner radius of the liner and $\delta(t)$ its thickness, we divide the liner into n layers (n can be as large as we please) of fixed mass, with the condition that the collision shock passes through each layer in equal time interval. Let $r_i(t)$ be the inner radius of the ith liner and $I_i(t)$ the current carried by it, and t_i be the time when the shock wave reaches $r_i(t)$. By definition, we have

$$t_i = t_s + \frac{i-1}{n}(t_e - t_s),$$

where t_s (t_e) is the time when the collision starts and ends. Between t_i and t_{i+1}, $\dot{r}_i(t)$ will have a jump given by

$$\Delta v_i = \dot{r}_i(t_{i+1}) - \dot{r}_i(t_i). \tag{5}$$

The inductance associated with $I_i(t)$ is simply

$$L(r_i) = L_0 + L_\ell log[r_0/r_i(t)]. \tag{6}$$

Therefore, for a liner of finite thickness the last term of Eq.(1) should be replaced by

$$F(t) \equiv \frac{d}{dt}\sum_{i=1}^{n} I_i(t)L(r_i).$$

Carrying out the time derivative explicitly, we get

$$F(t) = \sum_{i=1}^{n}[\dot{I}_i(t)L(r_i)] - L_\ell\sum_{i=1}^{n}[I_i(t)\dot{r}_i(t)/r_i(t)]. \tag{7}$$

By the same argument used earlier, we can assert that $F(t)$ is a continuous function since $r_i(t)$ and $L(r_i)$ are.

Let us define the differential for any function $f(t)$ as

$$\Delta f(t) \equiv f(t) - f(t_s) \tag{8}$$

for $t_s < t \leq t_e$. Since the collision interval $\Delta t_c \equiv t_e - t_s$ is very short, the time variation of any continuous function within Δt_c is negligibly small. To get the jump condition for $\dot{I}$, we expand $\Delta F(t)$ by the chain rule using Eq.(7) and neglect the differential of all except those functions that have a jump. Thus we get

$$\sum_{i=1}^{n}\Delta\dot{I}_i(t)L(r_i) = L_\ell\sum_{i=1}^{n}[I_i(t)\Delta v_i/r_i(t)]H(t-t_i), \tag{9}$$

where the function H is defined by $H(t) = 0$ for $t < 0$ and $H(t) = 1$ for $t \geq 0$. The H function ensures that only those layers which have been decelerated by the collision shock before t can contribute to the jump. Since the liner thickness is much smaller than the radius, we can set $r_i(t) \approx r(t)$ and likewise $L(r_i) \approx L(r)$. For $t_s < t \leq t_e$, we can further use $r(t) \approx r(t_s) \equiv r_c$ and $L(r(t)) \approx L(r_c)$ and rewrite Eq.(9) as

$$\Delta\dot{I}(t) = \frac{L_\ell}{r_c L(r_c)}\sum_{i=1}^{n}[I_i(t)\Delta v_i]H(t-t_i). \tag{10}$$

We can now take the limit $n \to \infty$, and the sum over i becomes an integral over x, which is the radial distance traveled by the shock

$$x(t) = \int_{t_s}^{t} v_s(t')dt',$$

where v_s is the shock speed. Let $j(x,t)dx$ be the current carried within dx and $v_i \to v(x)$, we finally arrive at

$$\Delta\dot{I}(t) = \frac{L_\ell}{r_c L(r_c)}\int_0^{x(t)} \Delta v(x')j(x',t)dx'. \tag{11}$$

Let us make a few comments on the above equation. First, for a liner of finite thickness the jump in $\dot{I}$ is no longer instantaneous but rises sharply and continuously during the collision interval. Second, in the simple case when the density and current are uniform across the liner thickness so that v_s, Δv, and j are independent of x, we have $x(t) = v_s(t - t_s)$ and $\Delta\dot{I}(t)$ rises linearly in t as

$$\Delta\dot{I}(t) = \frac{I(t)L_\ell}{r_c L(r_c)}\Delta v[(t - t_s)/\Delta t_c]. \tag{12}$$

This implies that $\Delta\dot{I}(t_e)$ has the same value as given by Eq.(4), even though the jump is not instantaneous.

In the liner-ejecta experiments, the liner remains solid before the first collision, so we expect v_s to be constant. Using $r_c = 1.54$ cm, $L_\ell = 4.6$ nH, $L(r_c) = 35$ nH, and the averaged value for $\Delta\dot{r} = 2.8$ km/s as calculated by the RAVEN simulation, Eq.(12) gives us $\Delta\dot{I}(t_e) = 0.99 \times 10^{11}$ A/s. This estimate is in excellent agreement with the code result .98 $\times 10^{11}$ A/s read off from dI/dt.

We now also understand why the peak of each jump is slightly after the onset of each collision. The delay is simply the transit time for the collision shock to travel to the outer liner surface. At the first collision, the shock needs only to pass through the solid liner. We can use the liner-target collision velocity 3.6 km/s to calculate the shock velocity to be 7.7 km/s, which takes 83 ns to pass through the liner thickness. This is again in good agreement with the time delay inferred from the code simulation. At the second collision, however, the shock has to traverse both the target and the liner. The combined thickness would now be about four times the liner thickness at the first collision due to additional thickening because of the smaller radius and considerable expansion caused by shock heating. This fact explains why the second jump has a much longer rise time than the first, as seen both in the calculation and experimental data.

Diagnostic Applications

Now that we have established the physical mechanism for the sharp jump in dB/dt, we can utilize this effect as a valuable tool in the following diagnostic applications:

1. Before the discovery of B-dot jumps, we relied on the x-ray radiographs to estimate the experimental collision time. We first measured the distance between the liner and target from the radiograph and then used the calculated velocity to obtain the extra time. The typical uncertainty is about 30 ns. The B-dot jump provides us not only a direct but also more accurate (about 10 ns in accuracy) measurement of the collision time.

2. In our liner-ejecta experimental series, we have to trigger the holography laser about two μs after the liner-target collision in order to observe the ejecta that are moving inside the collimator. If we miss the timing by more than 0.2 μs, we will not be able to observe the complete velocity spectrum of the ejecta. In the past, we used the preshot calculation to set the holography trigger time, which is tied to the start time of the driving current. However, due to experimental uncertainties in setting the bank voltage and in the liner mass, the actual collision time has a standard deviation about $\pm$70 ns over many shots. Since the first jump in Fig.1 is a built-in time mark for the liner-target collision, it can be used as a reliable fiducial trigger for the holography laser and other diagnostics that follow this time. We have demonstrated the feasibility of such a scheme. A 1.3 MHz high pass filter of the B-dot signal was used to remove low frequency components. By gating our trigger system past the early oscillations, we have successfully triggered on the jump signal. We plan to apply this technique on the upcoming liner-ejecta experiment to trigger the holography laser.

3. With improved time resolution in the B-dot data, the shape of the jump profile can provide us a valuable benchmark to check against the MHD code calculations.

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1. R. L. Bowers *et al.*, these proceedings.

2. M. Hockaday *et al.*, these proceedings.